Simulation and characterisation of low gain avalanche detectors for particle physics and synchrotron applications

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Outline

- **Motivation for LGADs**
- **Introduction to LGADs**
- **Process Simulation Results**
- **Device Simulation Results**
- **Overview of Fabricated Wafers**
- **Laser Characterization for TCT**
- **Results for Runs 1**
- **Results for Run 2**
- **Summary**

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Motivation

- Our aim is to be able to detect low energy x-rays in the region of 1 keV
- Penetration depth of a 1keV photon in silicon $\approx 3\mu$m.
- Medipix 2 and Timepix 1 have a noise level of roughly 4-4.5 keV
- Timepix 3 has a noise level of roughly 2 keV
- Medipix 3 has a noise level of roughly 3 keV
- In order to detect such a photon an internal gain of around 5-10 is needed.
- Hence the study and fabrication of LGAD's is very interesting to us.

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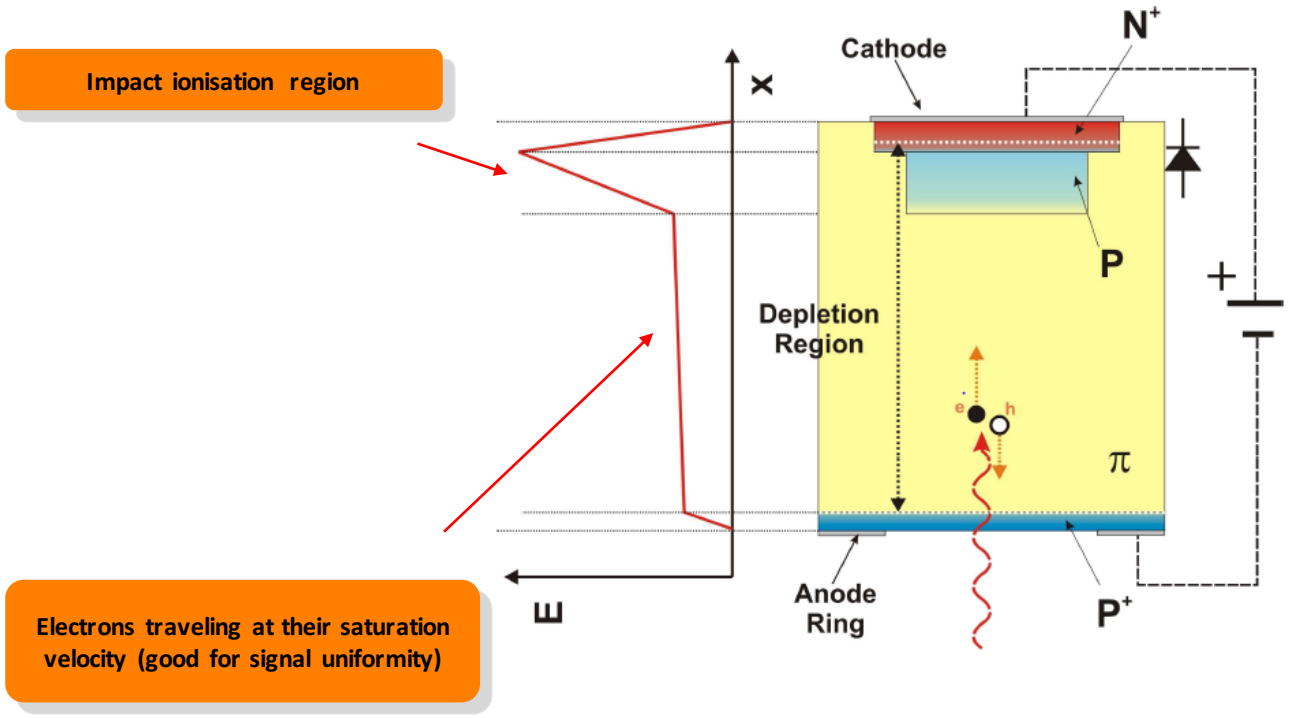
Basic LGAD structure



Taken from a talk by Dr. David Flores of CNM given at SIM detectors in LPNHE in 2014

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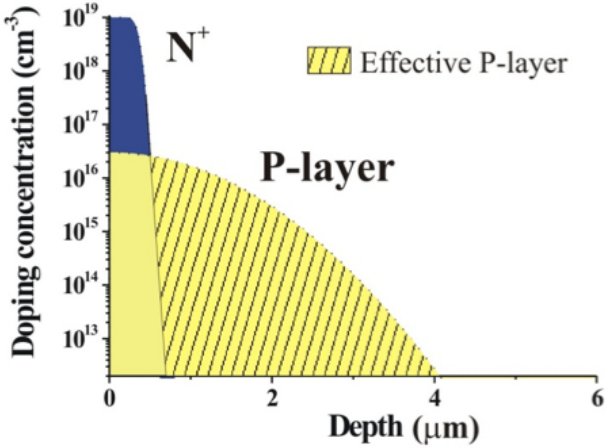
Process Simulation

- Process Simulation performed using Synopsis Sentaurus TCAD software.
- Full fabrication flow simulated using Micron Semiconductor's existing recipe for a PIN diode.
- Simulations were performed to introduce the multiplication region underneath the anode.
- Existing LGAD design's were used as a guideline for the profile of the multiplication region, where the depth of the doping profile is controlled by the drive-in time.
- Doses in the range of 5e12-2e13 were used in 1D simulations to obtain a suitable profile.
- Subsequently 2D devices were simulated to obtain a more realistic gain value.

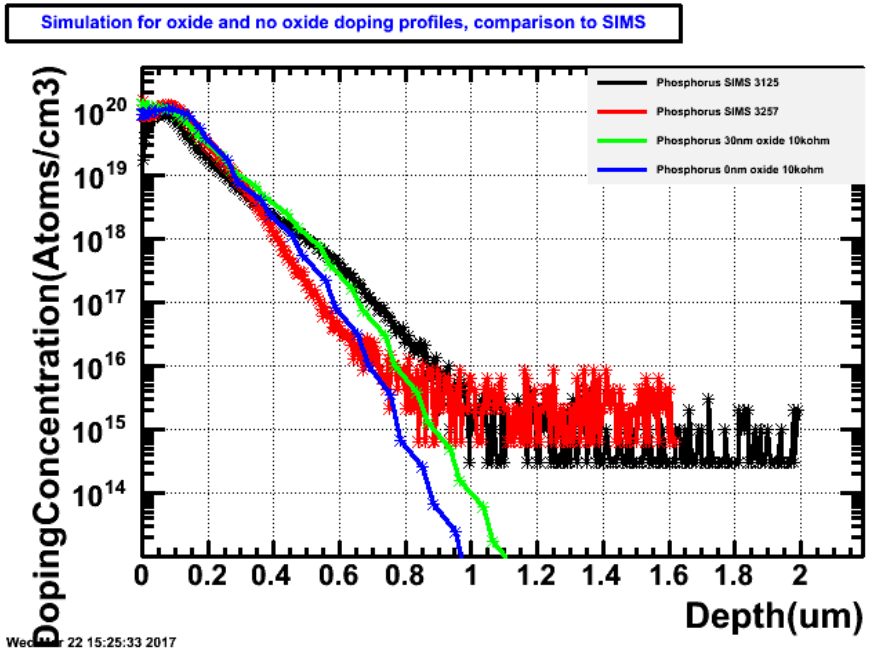


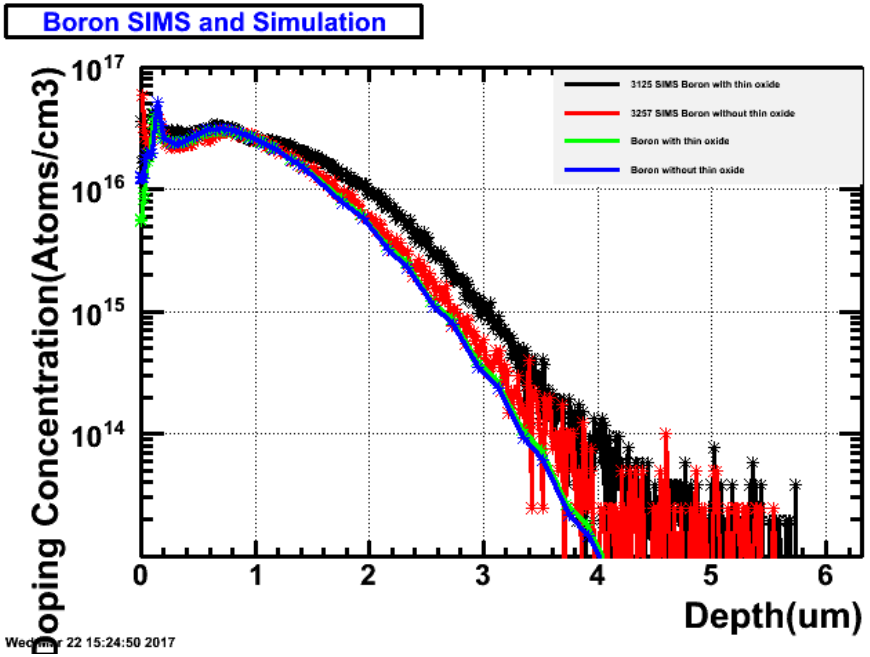
Gain estimation of RT-APD devices by means of TCAD numerical simulations ,I.Cortez et al, 2011

SIMS

- SIMS measurements from two different runs
- Simulation shows strong correlation to SIMS.
- Difference between runs is the presence of a thin oxide before the junction implant.

- Boron profiles vary slightly from run to run.
- Improvements made in fabrication process to try to minimize variation and increase control of boron profile.





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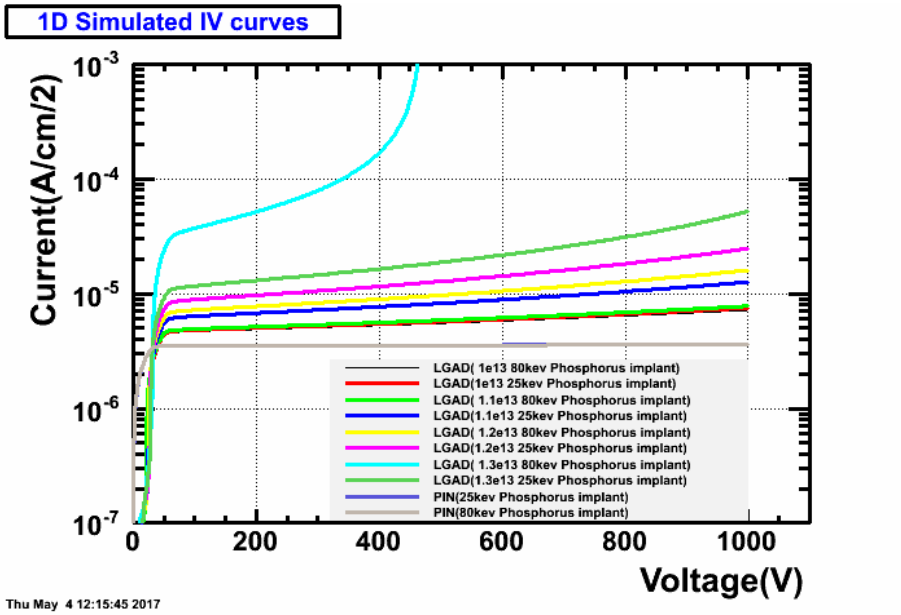
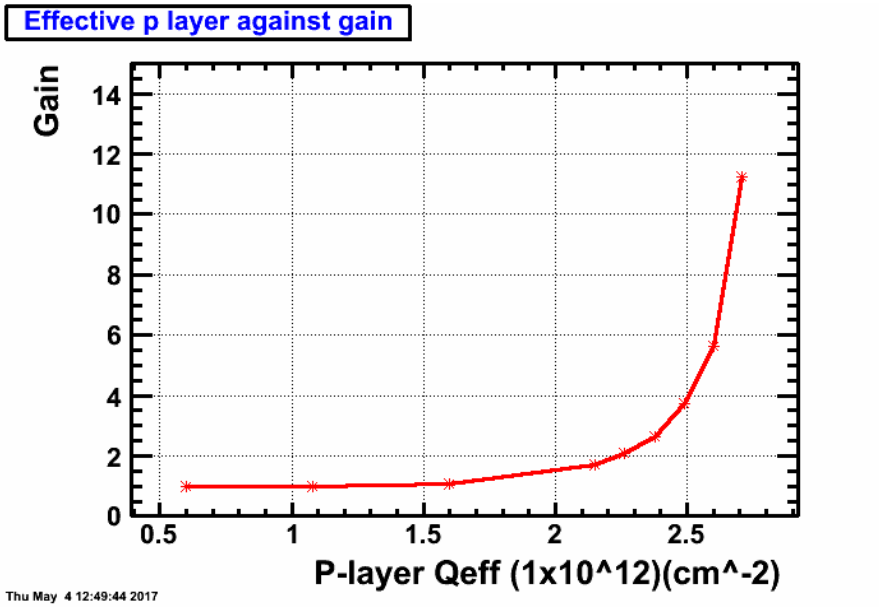
Device Simulation

- Device simulation performed using the Drift Diffusion transport model..
- Gain simulation performed by generating and collecting charge within the device.
- An initial charge distribution is introduced in the Sentaurus Heavy Ion model.
- The evolution of the generated charge is calculated by transient simulations
- All initial charges are deposited in the back side of device to replicate an alpha particle interaction.
- Simulation calculated to replicate CNM results for effective p layer dependence on gain for a 1D device.
- Control of implants is clearly of great importance.





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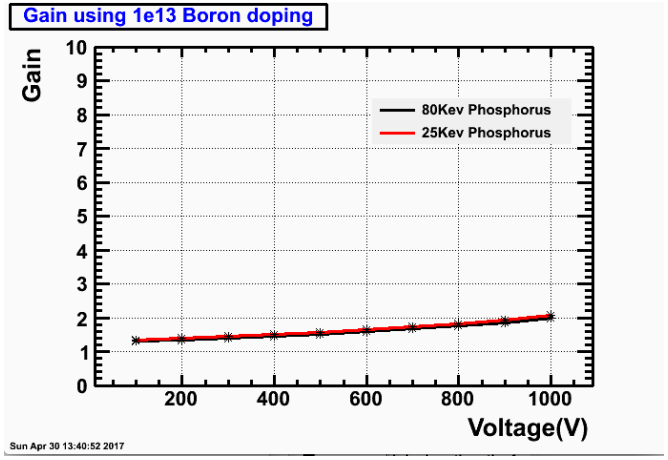
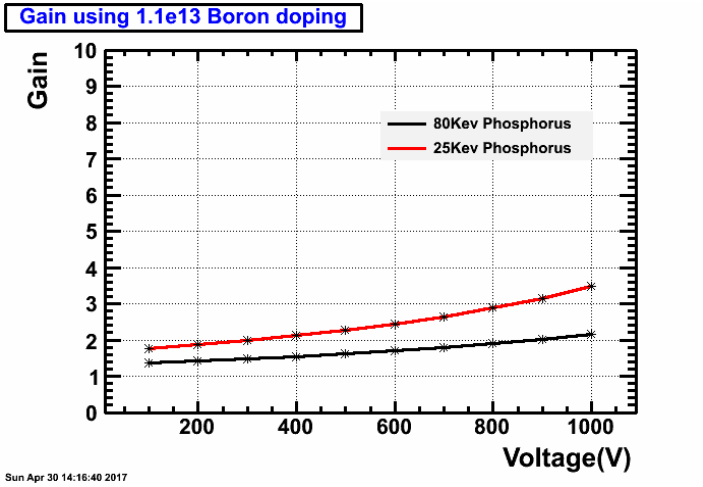
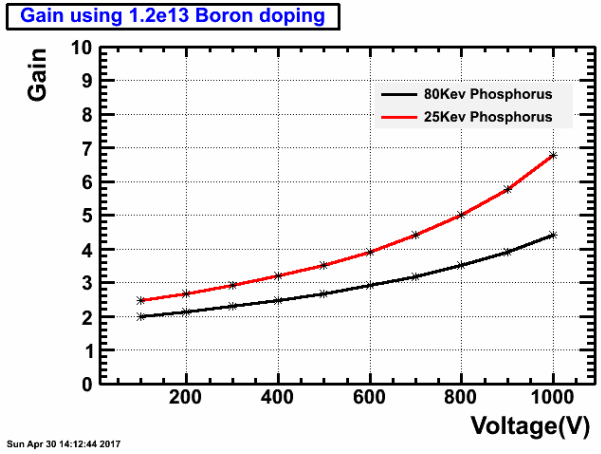
1D Device Gain Results

- Two parameters investigated.
- Boron dose and Phosphorus implant energy
- Increasing Boron dose increases gain
- But ultimately decrease breakdown voltage.
- Decreasing phosphorus implant energy increases gain.







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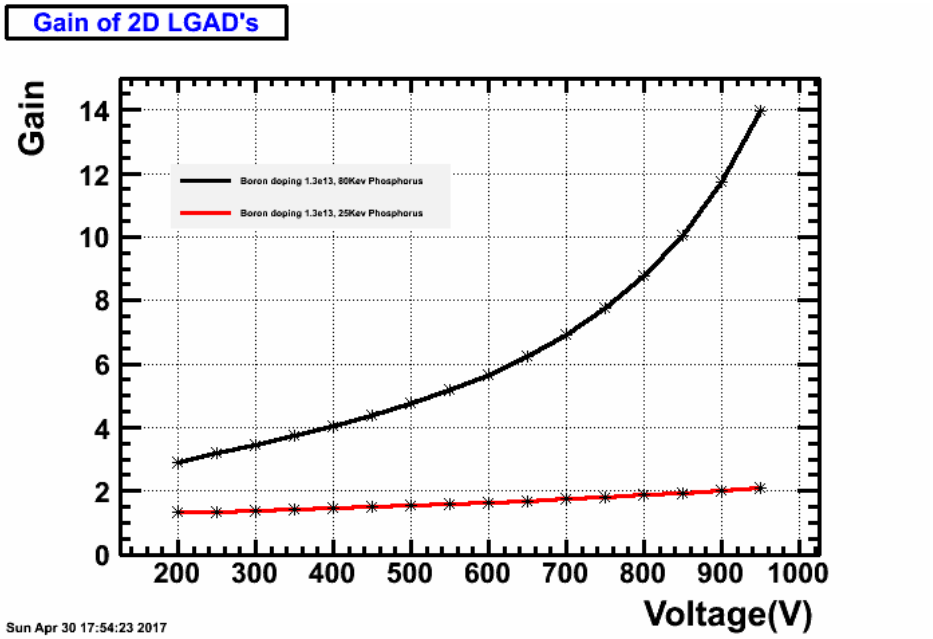
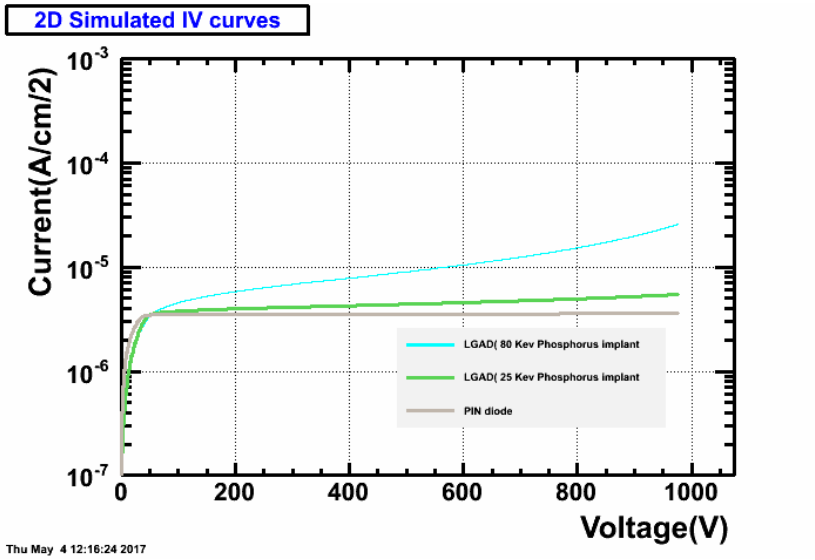
2D Device Simulation

- 2D device simulation using Boron dose of 1.3e13cm^{-2} as 1D simulations showed gain of interest in this region.
- Gain significantly reduced for 2D simulations compared with 1D simulation. Still unclear why this as both doping profiles are the same.
- Possibly due charge lose at junction edge





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Fabricated Devices

Wafer Run	Pad Size (mm)	Boron Doping Level (cm^{-2})	JTE	Phosphorus Implant Energy (KeV)
1	1x1, 2x2, 4x4, 5x5, 10x10	$5x10^{12}$, $1x10^{13}$	None	80
2	1x1, 2x2, 4x4, 5x5, 10x10	$1.3x10^{13}$, $1.6x10^{13}$, $1.9x10^{13}$	None	80
3	1x1, 2x2, 4x4, 5x5, 10x10	$1x10^{13}$, $1.1x10^{13}$, $1.2x10^{13}$, $1.3x10^{13}$	None	80
4	5x5	$1.3x10^{13}$	Yes	25, 80

- Two masks sets used.

Mask 1

- Has a variety of sizes of devices. All square diodes with multiple floating guard rings
- For each size of device there are three multiplication implant region sizes.
- These are 75%, 80% and 100% of the junction implant size.
- Device are metallized with a 50μm hole in the centre on the front and backside of the device for use with the Transient Current Technique (TCT).

Mask 2

- Has one size of device, 5x5mm.
- These devices include an additional Junction termination extension(JTE) as this has been shown to improve the IV characteristics.
- Also includes a spaghetti type metal layer in order to study charge variation across the device and ease the focusing procedure.

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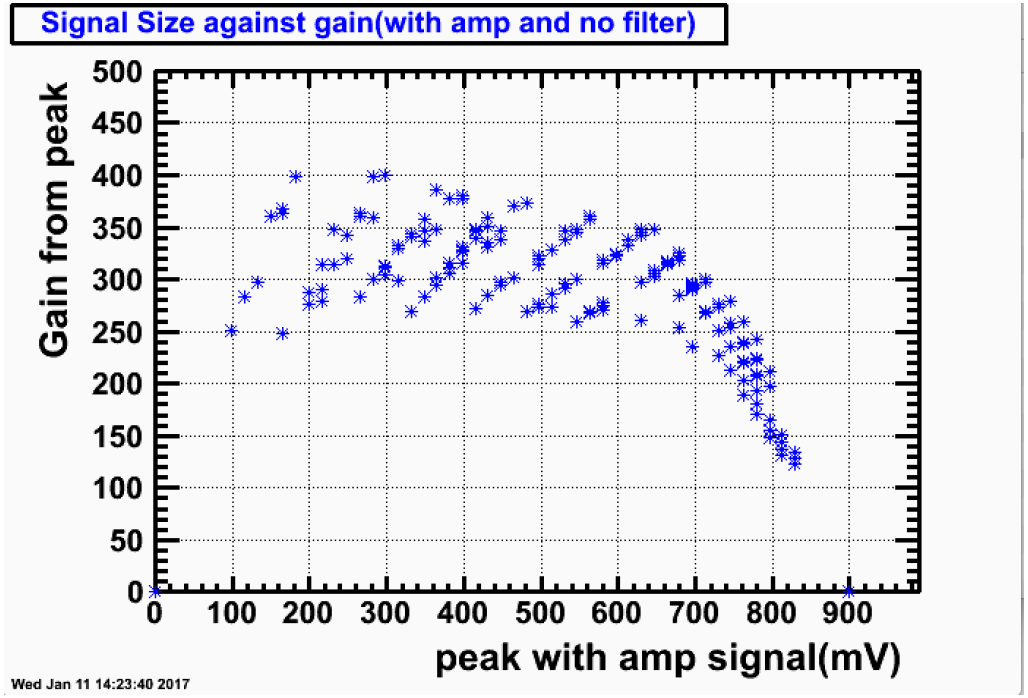
Laser Characterisation

- Before characterization of devices it was discussed that the set-up should be further investigated.
- The amplifier was studied in order to evaluate the true saturation voltage, where Particulars have quoted a saturation voltage of 900mV.
- A PIN diode was used with and without the amplifier to find peak value for a range of IR laser intensities.
- The gain was calculated by comparing peak value with and without amplifier.
- The saturation voltage could be determined when the gain value began to decrease.
- Gain should be in region of 300 as shown in figure to left.
- Gain not level which was surprising and needed further investigation.



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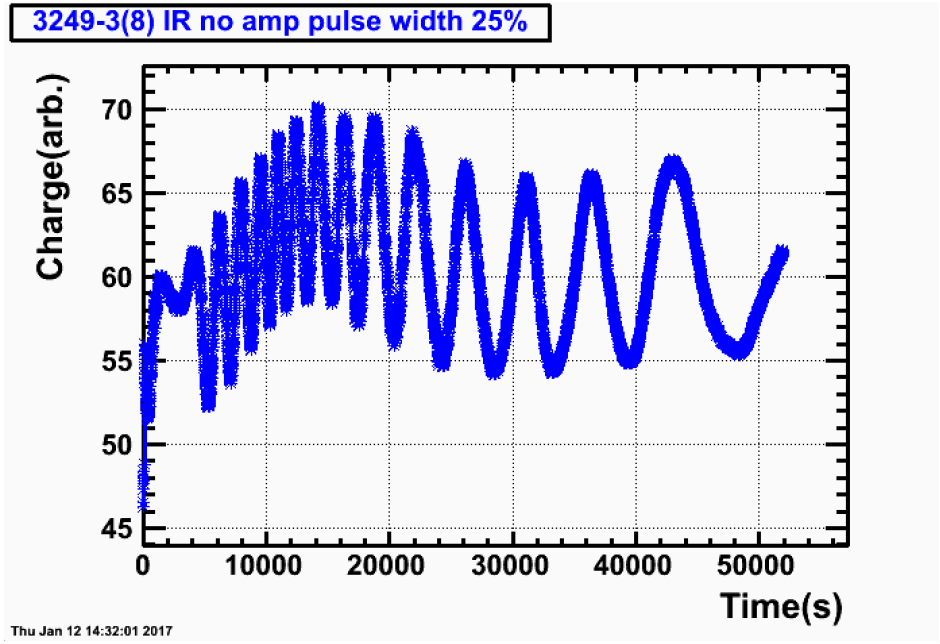
Charge output with time

- Charge collected from a PIN diode over time
- Can be seen that it varies with a low frequency sine type pattern.
- No correlation to temperature or humidity.
- This is seen on all devices tested, both LGAD and PIN diodes.
- Laser was sent for repair however pattern still observed.
- This pattern is not seen using the Red laser.
- This phenomenon not fully understood, but could be the result of beat of two low frequency signals.
- A beam monitor has been set-up but unable to normalise laser.
- Hence all results have been obtained using the red laser.



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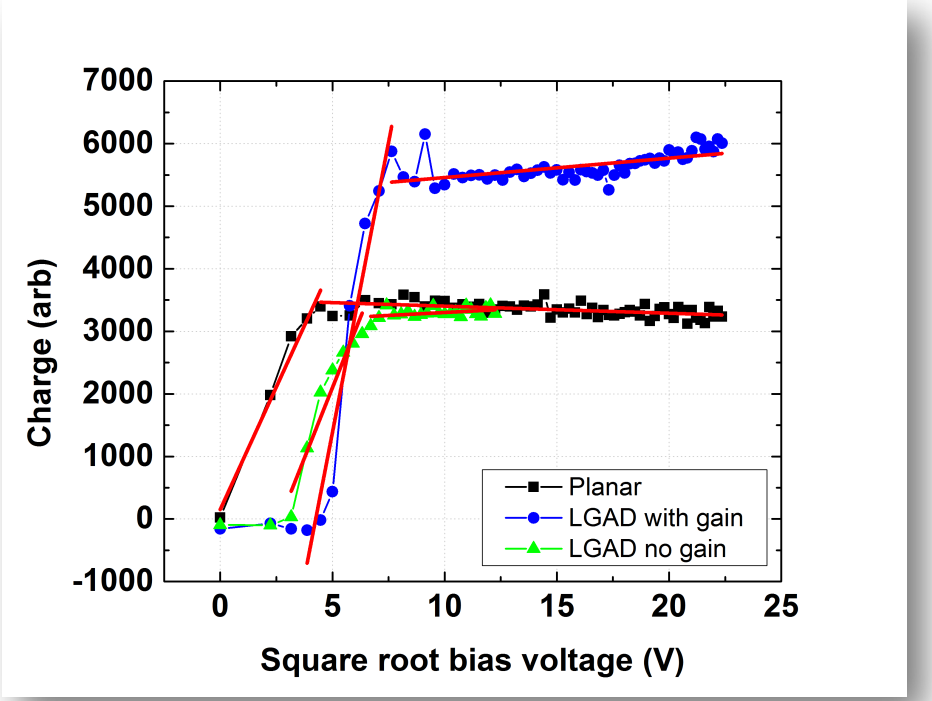
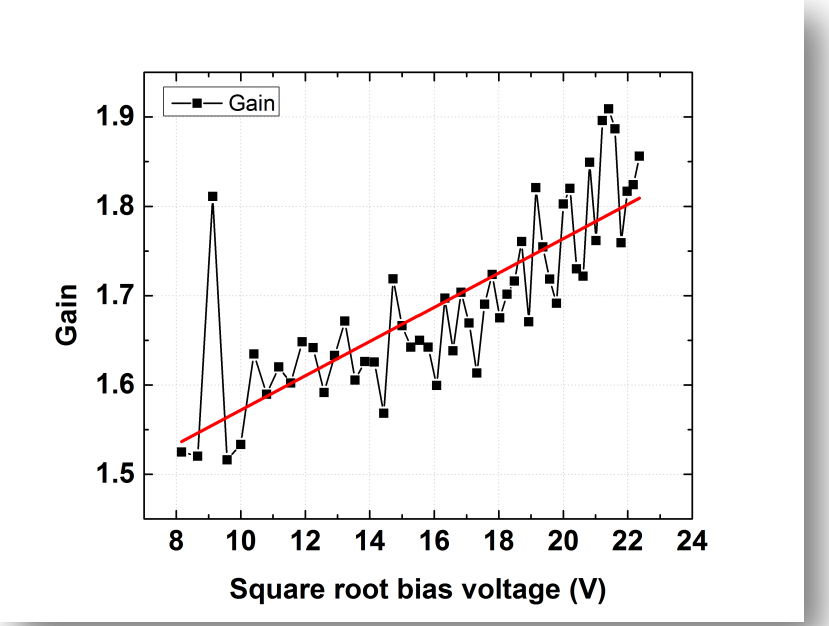
Run 1 Results from TCT

- Red laser(658nm) front illumination
- Penetration depth of 3μm in silicon
- Laser frequency of 5kHz, pulse width 72.5%
- Voltage range 0-500V
- Detector Thickness of 150μm and 200 μm
- TCT can determine full depletion voltage
- Can find collected charge and thus comparative gain





- Gain:
- Low Doped LGAD device = 0.95$\pm$0.03
- High Doped LGAD device = 1.69$\pm$0.03

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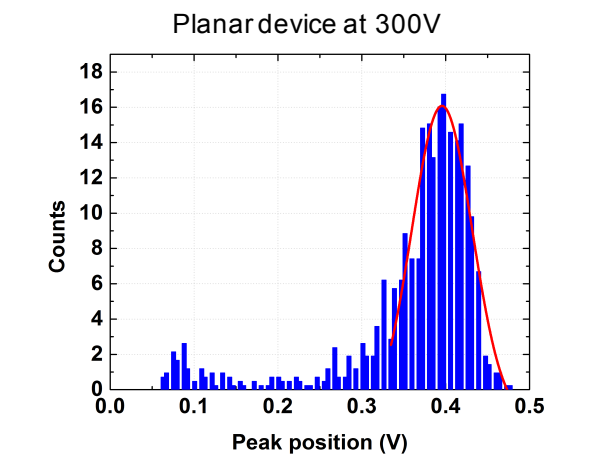
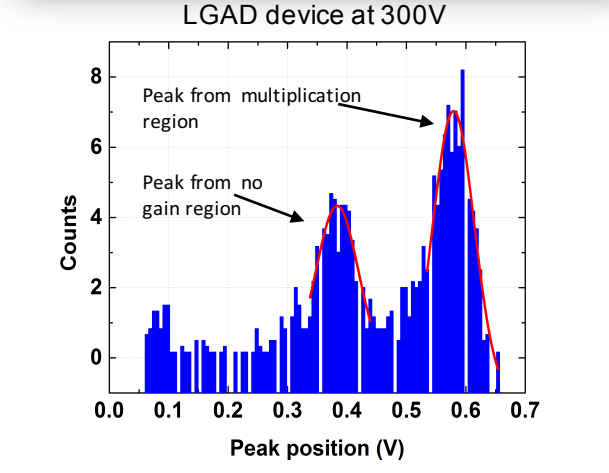
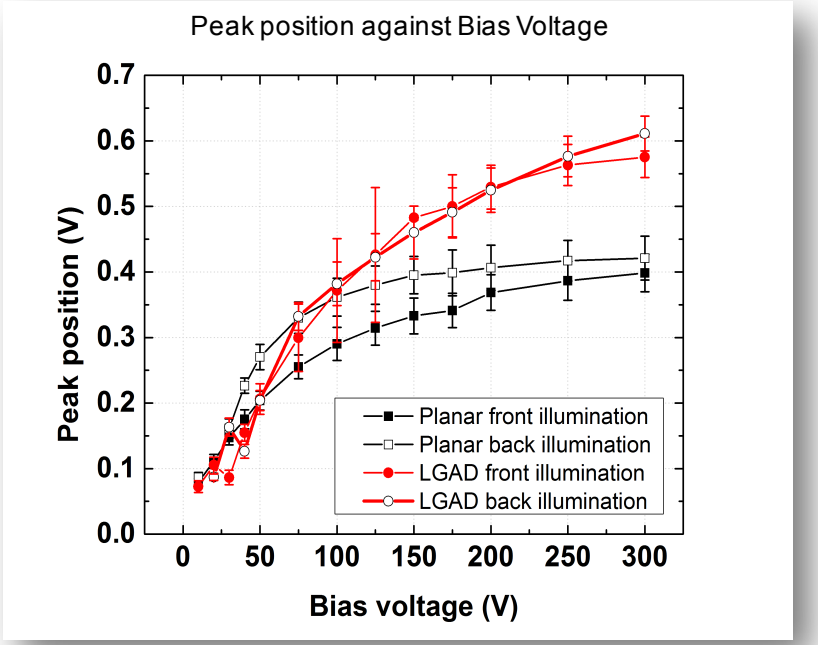
Run 1 Alpha TCT results





- Alpha Scans in Vacuum with Am^{241} source
- Voltage range 10-300V
- LGAD shows two peaks
- Gain Calculated at 300V comparing pin device with LGAD device.

- Gain from frontside illumination = 1.44 ± 0.03
- Gain from backside illumination = 1.45 ± 0.03
- At 300V gain from TCT = 1.44



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Conclusions from Run 1

- Expected gain from 1-D Simulation is around 1-2.
- Gain obtained from TCT and alpha scans was 1.69 and 1.45 at 500V and 300V respectively.
- Clear correlation between boron dose and gain.
- Compares strongly with the simulated results so simulation results can be trusted at this stage.
- For run 2 the boron dose was increased to hopefully increase the gain to the required level.

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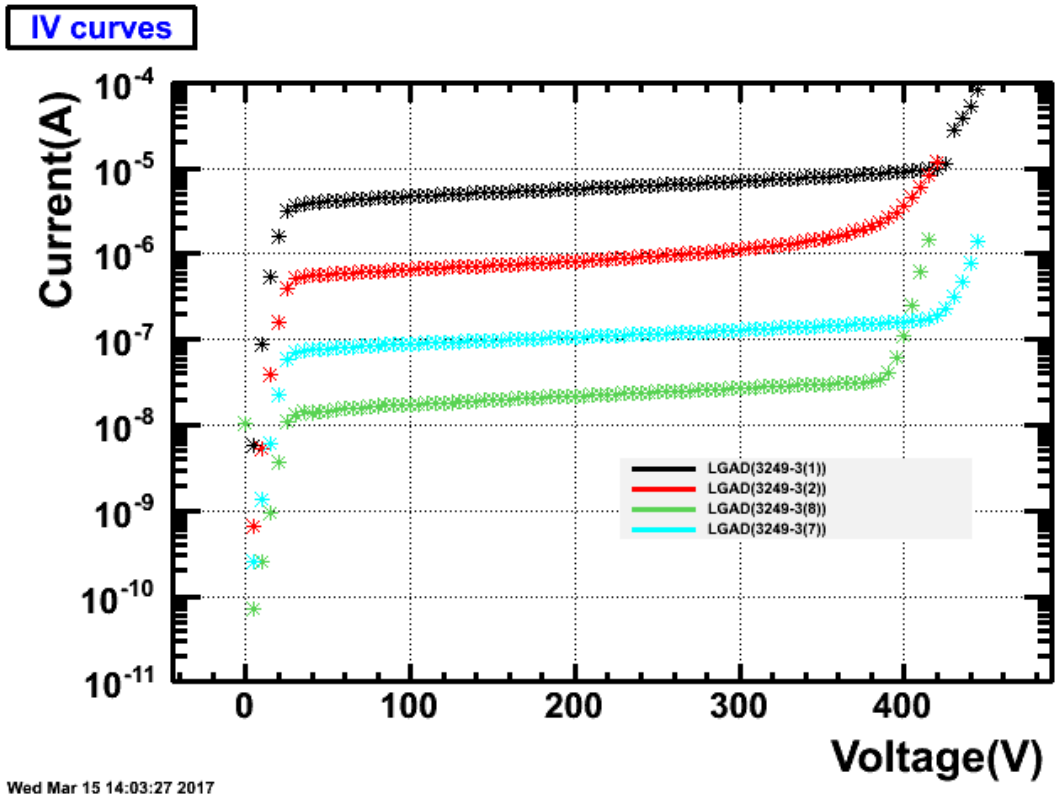
Run 2 IV characteristics

- Boron dose 1.3e13cm^{-2}
- Full depletion voltage ≈ 116V
- Breakdown voltage ≈ 400V
- Detector 3249-3(7)-Blue: This has a 1x1 active area with a p-layer of 75% of the total active area.
- Detector 3249-3(8)-Green: This has a 1x1 active area with a p-layer of 80% of the total active area.
- Detector 3249-3(1)-Black: This has a 2x2 active area with a p-layer of 75% of the total active area.
- Detector 3249-3(2)-Red: This has a 2x2 active area with a p-layer of 80% of the total active area.



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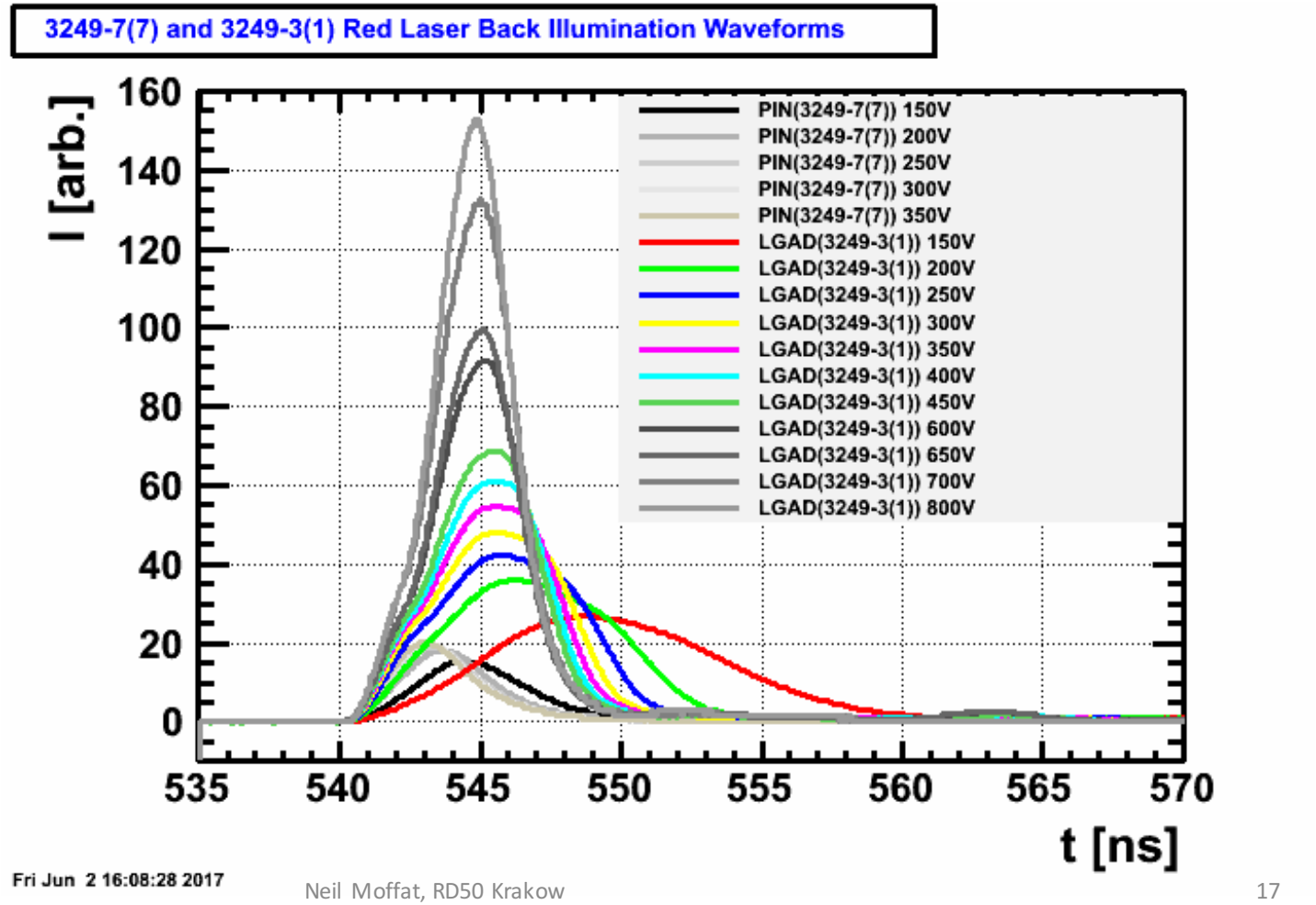
Detector 3249-3(1) WF

- Red Laser used, 1khz frequency.
- 2% Pulse Width
- Charge calculated by integrating waveform.
- Gain obtained by comparing charge collected to a PIN diode.



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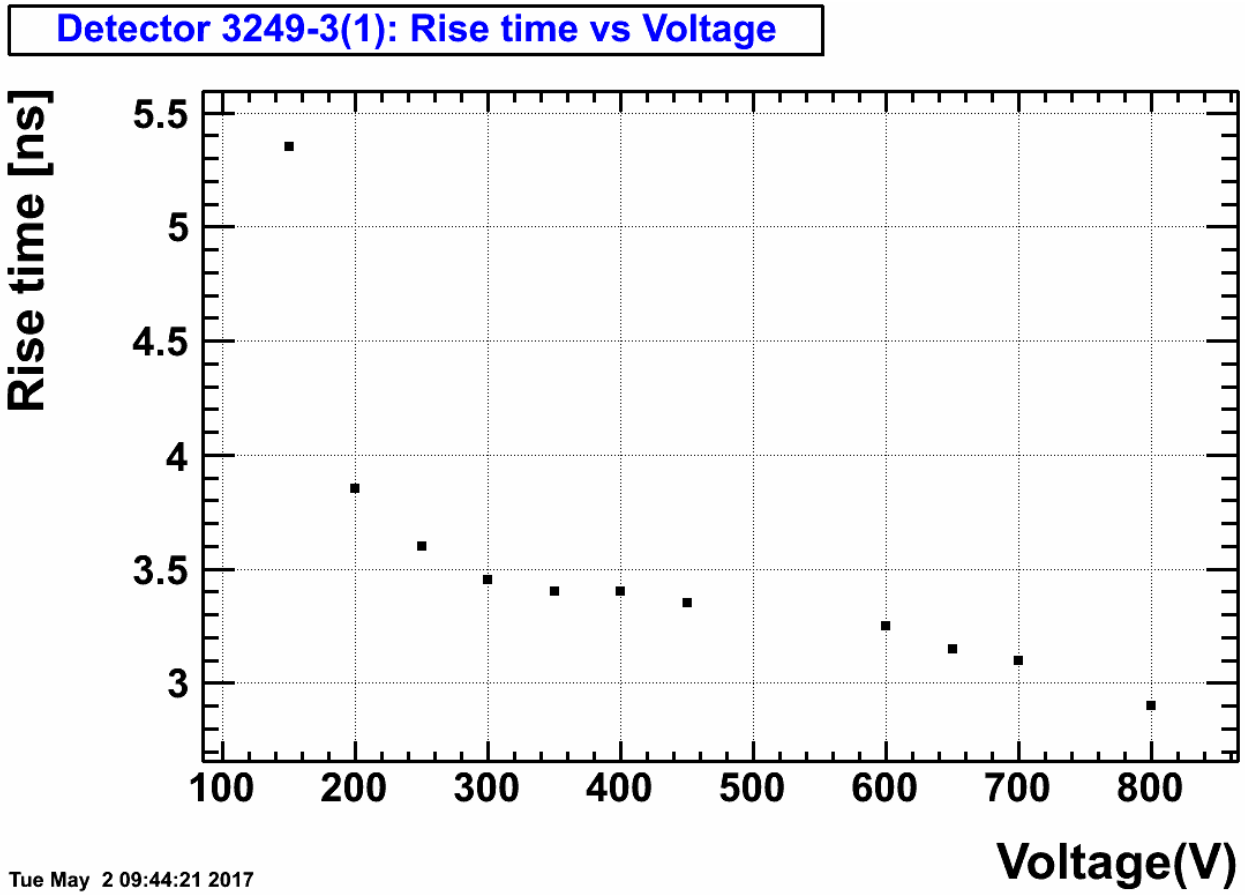
Detector 3249-3(1) RT



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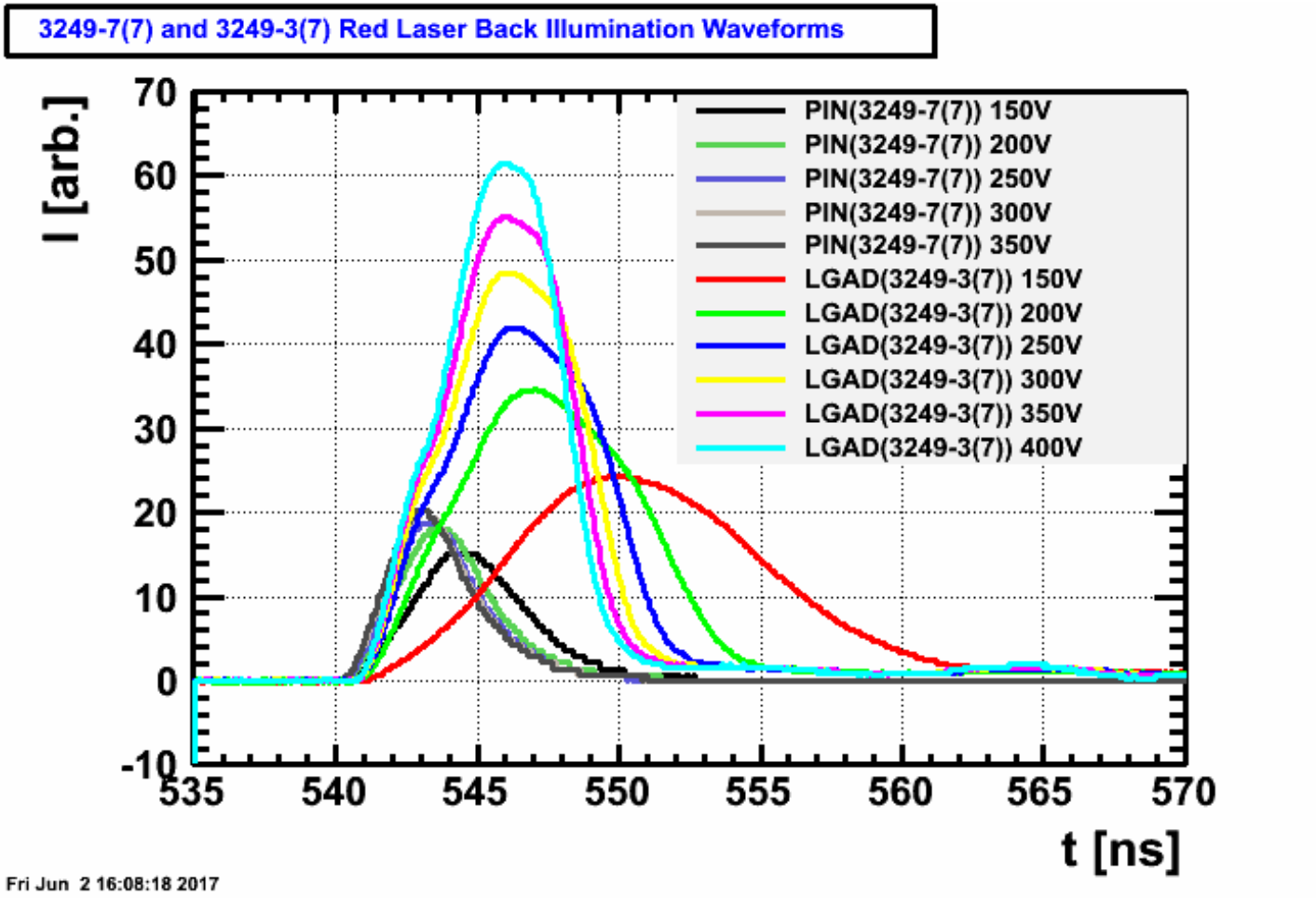
Detector 3249-3(7) WF



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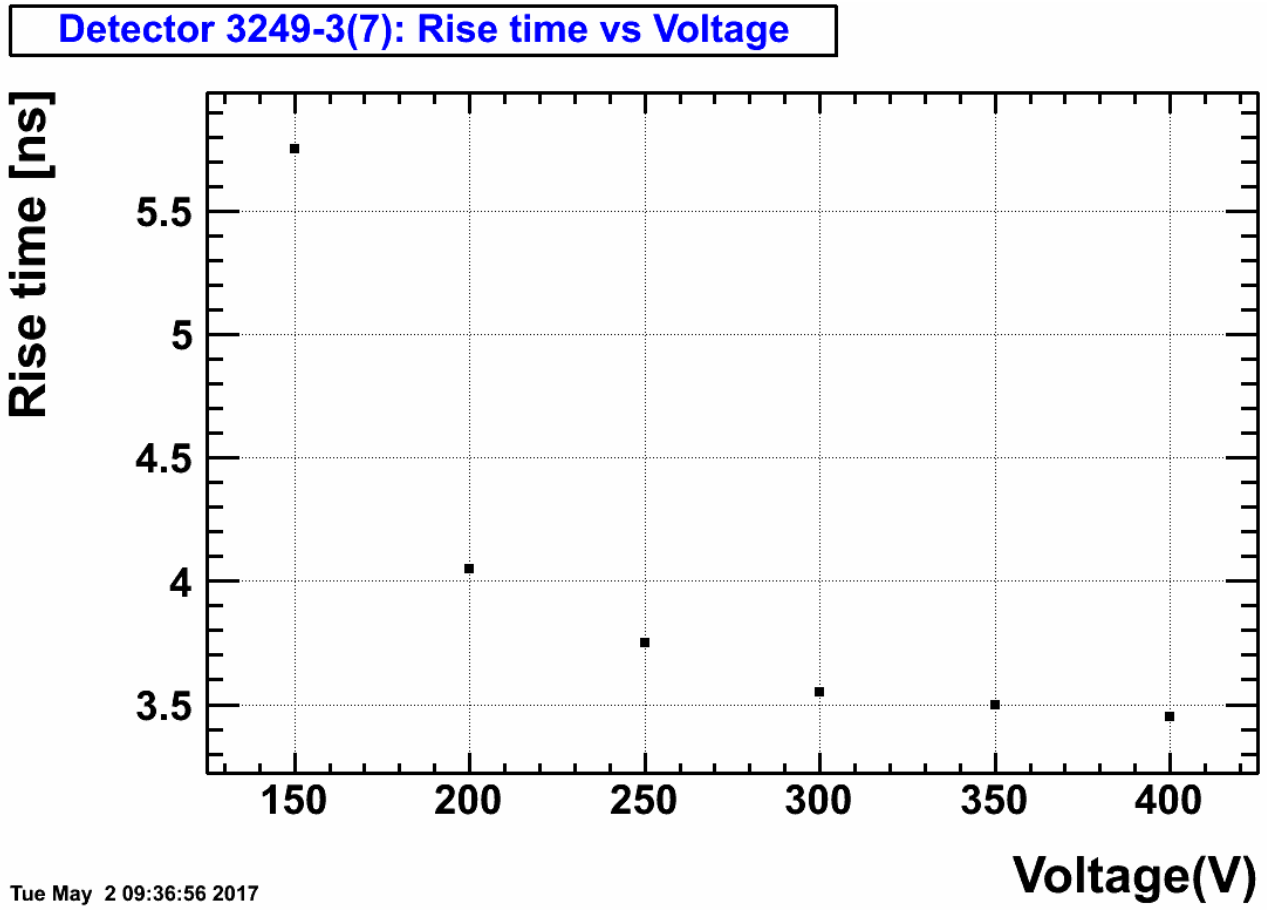
Detector 3249-3(7) RT



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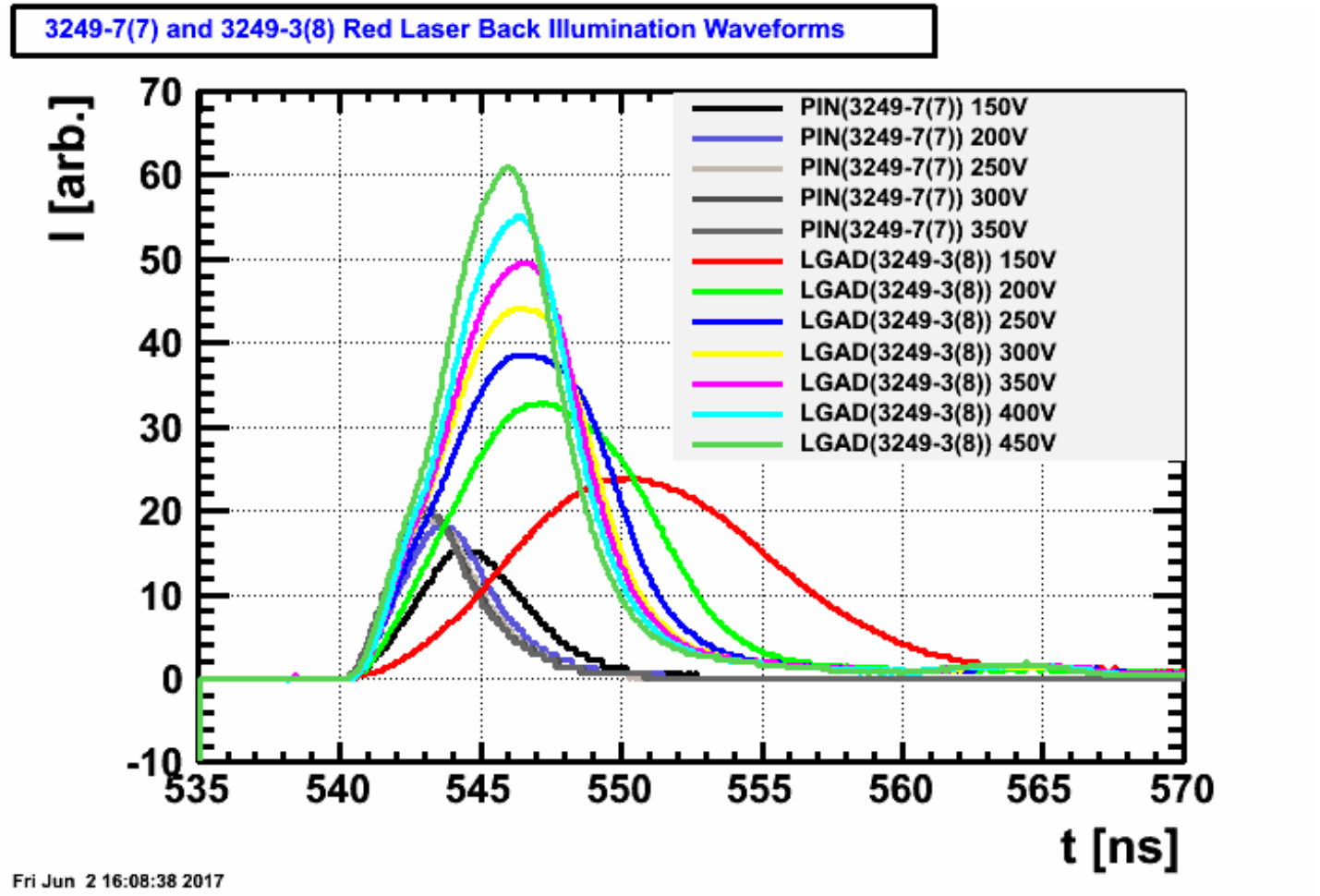
Detector 3249-3(8) WF



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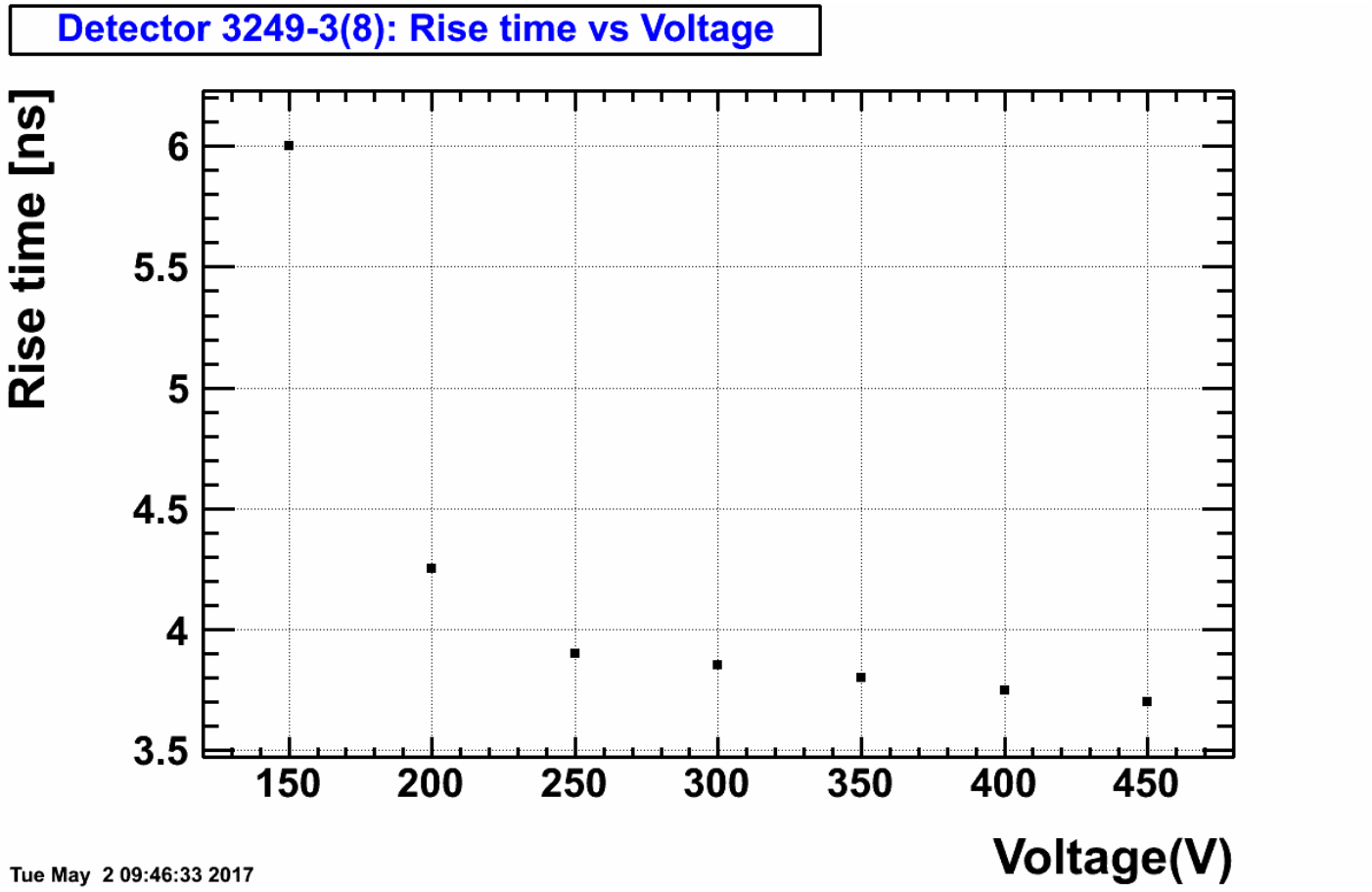
Detector 3249-3(8) RT



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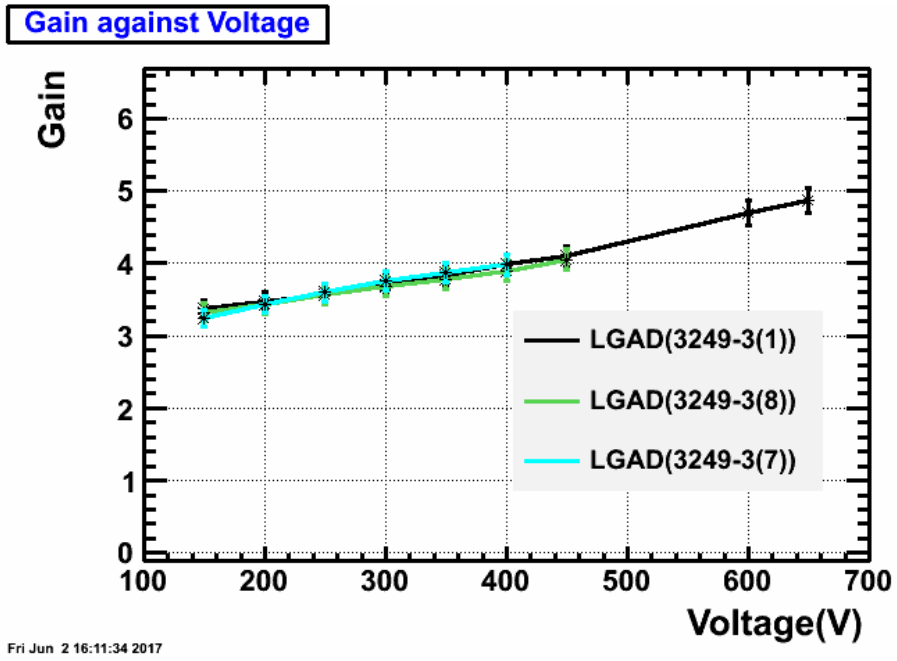
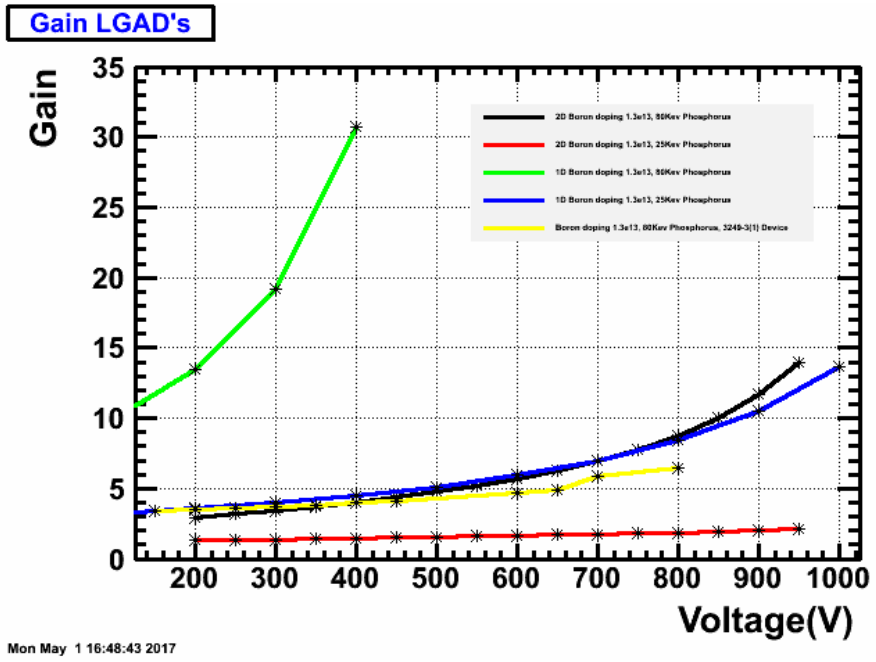
Gain Comparison



- Gain in range of $\approx 3-5$ for voltages 150V-650V
- All devices match within error.

- Device gain matches 2D simulation quite well.
- The Yellow line being the device under test and the black line the 2D simulated device.



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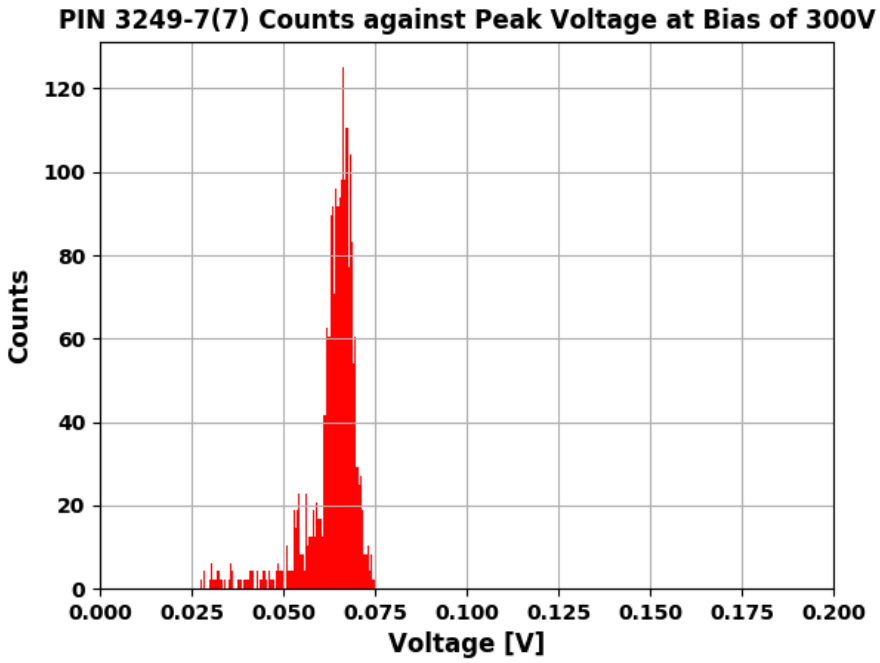
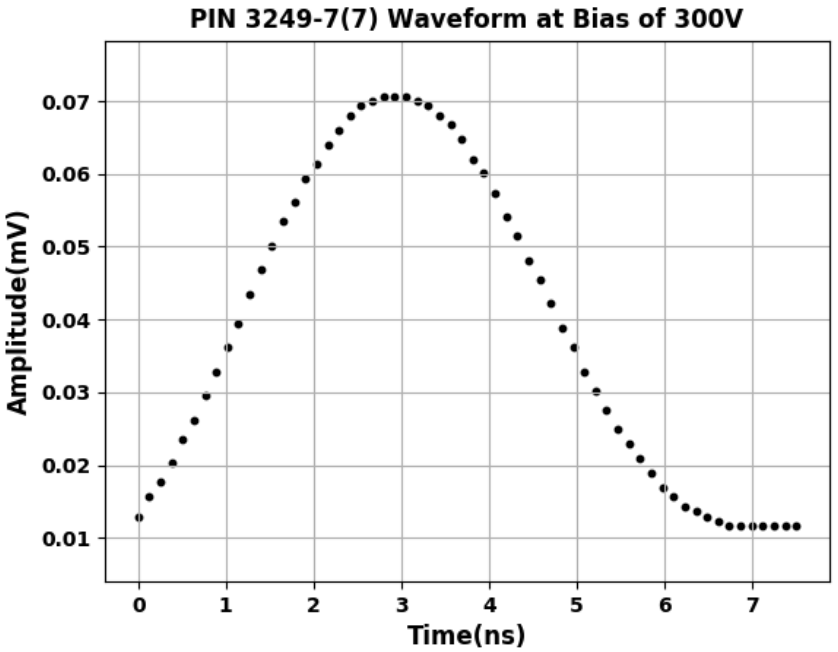
Alpha TCT PIN

- Alpha TCT using an Am^{241} source.
- Waveforms in peak region extracted and charge calculated by integrating waveform shown.





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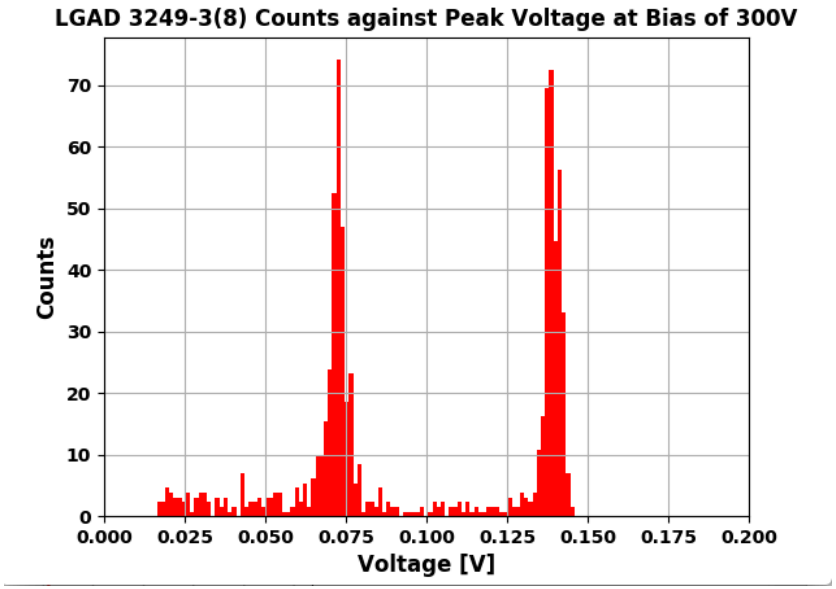
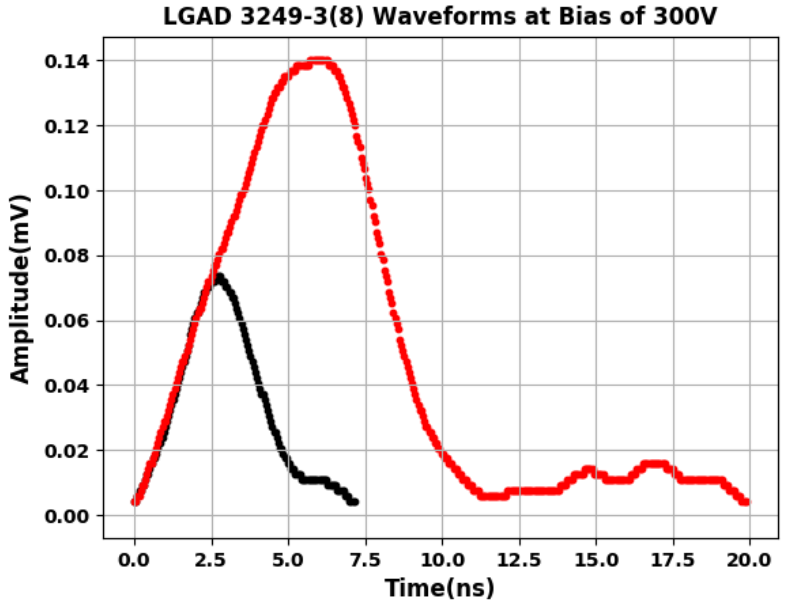
Alpha TCT LGAD

- When LGAD studied two distinct peaks can be seen.
- This is due to gain and non gain regions.
- Script run to extract waveforms from both peaks.



- Gain can be calculated from waveforms from one device.
- The gain obtained is 3.5 at 300V
- Gain calculated from comparison to a PIN diode is 3.99 at 300V.
- The gain obtained from Red laser TCT at 300V is 3.75.
- This is comparable to alpha results.



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Runs 3 and 4

- Runs 3 and 4 have been fabricated but have produced no working LGAD devices, with a breakdown voltage of 20V.
- Run 3 was fabricated using mask 1 with a range of boron doses.
- The results of run 3 can be explained by the change in phosphorus profile shown earlier, increasing effective p layer and decreasing breakdown voltage.
- Run 4 was fabricated using mask 2, where there is an additional JTE implant and two phosphorus implant energies.
- Run 4 is still yet to be explained still awaiting SIMS results.
- Should hopefully have these in the next few weeks.
- Run 4 still has around 6 wafers yet to be fabricated, awaiting results from SIMS measurements to proceed with fabrication.

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Summary

- Expected gain from Simulation is slightly higher than the achieved value.
- The gain obtained from TCT and alpha scans was for run 1 were 1.69 and 1.45 at 500V and 300V respectively.
- The obtained from laser TCT for run 2 is the range of 3-5 for a Bias range of 150-650V.
- Preliminary results show the gain at 300V from Alpha TCT is the range of 3.5-4.
- It is possible to obtain a gain value without comparison to a PIN diode using alpha TCT.
- Future devices will include a JTE implant to lower leakage current.
- Next batch should be completed by July.
- The goal is to design and fabricate pixelated devices to be bump bonded to a Medipix chip.